Expression of Interest for a Long Baseline Neutrino Oscillation Experiment Using a Main Injector Beam and a Large Magnetic Sampling Calorimeter

B.C. Barish[5†], R. M. Bionta[9], C. Bower[8], C.B. Bratton[2], F.S. Dietrich[9], S. Dye[1], W. Gajewski[4], K.S. Ganezer[6], A. Habig[8], P.G. Halverson[4], R. Heinz[8], Y. Ho[2], J.T. Hong[1], E. Katsavounidis[5], E. Kearns[1], M.N. Kreisler[9], W. Kropp[4], J. Learned[7], W. Lee[2], G. Liu[5], R. Liu[5], N.P. Longley[5], Y. Lu[11], M. Masuzawa[1], D.G. Michael[5†], L. Miller[8], S. Mrenna[5], S. Mufson[8], M.J. Mugge[9], J. Musser[8], C. Okada[1], H.S. Park[9], C.W. Peck[5], L. Price[4], F. Reines[4], K. Scholberg[5], V. Stenger[7], J. Stone[1], M. Vagins[10], K. van Bibber[9], C.W. Walter[5], R. Webb[11], T.J. Wenaus[9], J. Wilkes[12], D.M. Wright[9] and C.R. Wuest[9]

1) Boston, 2) Cleveland State, 3) Columbia, 4) Irvine, 5) Caltech, 6) Cal. State Dominguez Hills, 7) Hawaii, 8) Indiana, 9) Livermore, 10) Louisiana State, 11) Texas A&M, 12) Washington

†Contact Persons

Abstract

A very large (nominally 17 KT) fine-grained, magnetic sampling calorimeter is discussed for use in studying events induced by accelerator or atmospheric neutrinos for the purpose of searching for neutrino oscillations. This detector allows a number of possible signatures for neutrino oscillations based on disappearance of muon neutrinos, ratio of neutral current to charged current events and appearance of tau or electron neutrinos by additional electromagnetic showers or apparent 'neutral current' events giving hadronic showers in the detector. Most importantly, the detector can provide an unambiguous signature of tau appearance using the muon decay channel of the tau, particularly if a narrow-band beam is employed.

The proposed detector will also represent a major stand-alone underground detector facility for non-accelerator physics. Atmospheric neutrinos can be collected during the same period as beam measurements are made and allow an extension of sensitivity to smaller Δm^2 using the ratio of neutral current to charged current events; a new physics signature for atmospheric neutrinos. In addition to the neutrino physics, a detector with these capabilities will also be able to extend current physics measurements on other non-accelerator topics including measurement of momenta for both downgoing and upgoing muons up to hundreds of GeV momentum, the most precise timing measurements ever achieved for a large detector for differences in arrival time of muons within a bundle, rough measurement of very high muon energies based on bremsstrahlung and pair production, search for very high energy muons at large zenith angles and other topics. In this document, we address primarily the long-baseline neutrino oscillation application of the proposed detector.

1 Physics Objectives

Observations by the Kamiokande and IMB collaborations on contained neutrino-induced events in their detectors suggest that perhaps as much as 40% of atmospheric muon neutrinos in the energy range from .2-1.5 GeV are missing. [1, 2]. The possibility of muon neutrino to tau or electron neutrino oscillations could explain the deficit. The atmospheric neutrino data suggest particular regions of mixing parameter space to explore. Figure 2 shows the regions of oscillation space which are allowed at the 90% confidence level from the Kamiokande measurements. Here, we assume that a minimum charge for a significant new experiment should be an ability to clearly observe neutrino oscillation signatures for the regions suggested by the atmospheric neutrino anomaly. However, we do not think that we should be limited to that region of parameter space. Rather, we wish to achieve sensitivity to the largest region of parameter space possible, given reasonable constraints on current accelerator beams and cost of the detector. We set a particular goal of reaching $\sin^2 2\theta = .01$ for large Δm^2 ('fully mixed'). However, because of the hint coming from the atmospheric neutrinos, we believe that marginal gains in sensitivity in parameter space should not come at the cost of excellent understanding of systematic errors in the region of the atmospheric anomaly.

The issue of systematic error in a long-baseline experiment is of crucial importance. Detectors which are far from an accelerator will necessarily be very large. The acceptance for some particular physics signature can be well understood by study of some small section of the full detector in an accelerator beam-test. However, it is unlikely that the acceptance for the full detector will be as well demonstrated as might normally be the case for an accelerator experiment. In addition, the extrapolation of neutrino beams to very large distances is not a 'well known and measured' technique. Detectors which are very distant from the accelerator typically will have significantly different beam spectra than those at near or intermediate distances. Small divergence effects which are normally of no consequence for near accelerator experiments will become important for the long-baseline experiment. This will impose an irreducible systematic error on an experiment which relies solely on ratios of events in near and far detectors. The uncertainty in the beam at the far detector will also give systematic uncertainty to any physics signature based on some absolute calculation of an expected number of events. Finally, any measurements made with the atmospheric neutrinos will always have a number of systematic errors arising from uncertainty in the direction, flux and energy of the incoming neutrinos.

In order to make the most convincing experiment possible, we take three basic approaches to measurement of neutrino oscillation parameters. First, we wish to make the measurement using a number of different physics signatures. Since the measurements all make use of the same beam, they are not completely free of correlated systematic error. However, the systematic errors for the different measurements will largely be uncorrelated. We should be able to require consistancy between the measurements. Second, whenever possible, we use ratios in order to limit the systematic errors involved in absolute normalizations. Finally, we wish to demonstrate clear appearance signatures for the neutrino flavor which the muon neutrinos have oscillated to. For electron neutrinos, this means identification of the electron in charged-current interactions. For tau-neutrinos, we know of no means of either explicitly reconstructing the tau mass or of observing a secondary vertex resulting from the tau decay in a very large detector. Hence, we resort to statistical means to identify tau appearance based on the different possible tau decay modes.

The physics signatures which we envision using for oscillation measurements are the following:

1. The ratio between the number of ν_μ CC events in a far detector compared to the number in a specific region of a near detector. Most of the remaining measurements can be compared for differences in a near detector and far detector.

2. The ratio between the number of ν_μ CC events which come from interactions within the detector

and which have interacted in the rock before the detector with a resulting muon coming into the detector.

3. Measurement of the differential energy spectrum of muons produced in ν_μ CC interactions in the detector using muon range in iron and magnetic measurement. (Note that this is effectively a ratio measurement.)

4. The ratio of events with hadronic showers but no apparent muon track (nominally NC events) to those with a muon track (ν_μ CC events). This ratio can be taken as a function of observed energy if desired. This measurement is a very powerful technique which allows not only a clear signature of muon neutrino dissappearance but also is sensitive to tau neutrino appearance due to taus decaying hadronically.

5. Number of hadronic events with no muon with various characteristics (energy, number of initial tracks, penetration of showers) compared to expectation based on the differential energy spectrum of the neutrino beam (both measured and calculated). Taus decay 66% of the time giving hadrons and (depending on beam energy) those hadrons can be more energetic, carry more total energy and be produced at relatively large laboratory angles compared to the typical hadrons from fragmentation of the struck nucleon. This allows statistical identification to be done between events with CC ν_τ interactions and NC interactions.

6. Statistical identification of ν_τ's via the τ decays to $\mu\nu\nu$ channel. This signal may require a narrow band beam for best study but there may also be measurements possible using quasi-elastic scattering events and transverse momenta. For the narrow-band beam, the analysis is based on cuts on the laboratory scattering angle of the muon, the fractional energy that the muon carries with respect to the nominal beam energy and the observed fraction of electromagnetic and hadronic energy compared to the nominal beam energy. This is likely the most convincing means of identification of tau appearance.

7. Ratio of ν_μ to ν_e events from atmospheric neutrinos (contained events) up to about 10 GeV. Also ratios of contained events versus zenith angle for ν_μ events. Finally, a very large mass detector will be able to add the ratio of NC to CC events for the atmospheric neutrinos... a completely new measurement on those neutrinos.

It should be noted that even if no effect is observed in the accelerator beam experiments that the atmospheric anomaly may still persist. Since the detector for a long-baseline experiment must have many of the properties that would be useful for measurements on atmospheric neutrinos as well it seems advantageous if the detector is placed in a deep-underground location where it will be possible to make the measurements on the atmospheric neutrinos along with the beam measurements. In addition to the measurements on atmospheric neutrinos, such a detector could be used for other types of studies on penetrating cosmic rays. These subjects include the measurement of muon momenta for upgoing and downgoing events up to a few hundred GeV by use of the magnetic bending of these tracks. For the upgoing events, this would add very significant new knowledge to the atmospheric neutrino spectrum. For downgoing events, these measurements could be useful in confirming interaction models of the primary cosmic rays. Likewise, the magnetic bending will allow a measurement of the sign of the charge of the muons for which the ratio is related to the ratio of matter and antimatter in the primary cosmic rays. This detector also has a rough ability to make energy measurements of TeV and higher energy muons based on bremsstrahlung and pair production. This can be employed in studies of downgoing muons and in a search for horizontal muons coming from neutrinos originating from a point source such as an AGN. Good timing capabilities (on order 1 ns resolution per plane) could allow for unprecedented resolution in the measurement of the time of arrival of muons within a single bundle. This can be used in searches for heavy particles which decay to muons or could also be used for studies of cosmic ray interactions. On the other hand, there could be advantages in using fast extraction timing to allow surface construction for the detector and we intend to make a comparative study before making a final decision.

2 The Detector

An optimal detector for making the measurements described in the preceding section must have very large mass, probably should be deep underground, be located a sufficient distance from the neutrino source to have good sensitivity in Δm^2 and have fine-grained readout so that details of events can be studied. It should be possible to identify and measure large electromagnetic showers caused by an electron within a background of showering hadronic fragments. It should be possible to clearly identify muons and measure their momenta and angle of production in the laboratory with respect to the direction of the beam. An important part of this ability is the complete absorption of hadronic showers implying a large number of hadronic interaction lengths along the axis of the beam. Good (not necessarily excellent) hadronic and electromagnetic energy resolution are important. The ability to separate showers from electrons from those induced by π^0 decay is attractive but may be difficult to achieve with a very large detector. We propose that a detector based on a magnetic sampling calorimeter with fine-grained lateral and longitudinal separation is the best means of meeting these requirements for a reasonable cost and with solid expectation of the ability to complete the project in a timely manner. In order to achieve the largest possible mass for lowest cost, the granularity of the detector should be scaled to match the energy scale of the neutrino beam which is to be used. In particular, since we are focussing on measurements with neutrinos of multi-GeV energies, we propose a detector of granularity appropriate to the processes at this energy scale.

Such a detector can use several possible technologies to achieve the stated physics goals. We plan to explore several options for the construction. The sampling calorimeter approach allows for a broad range of trade-offs in sensitivity versus cost. Here, we present some of the possibilities. We will discuss the relative advantages in the different approaches. Further study and development is needed in order to arrive at a final, optimized proposal. The scale of the detector is set by the statistics necessary to reach the level of 1% oscillation probability. If we take the ratio of NC/CC events as the benchmark test, then we would need a minimum of about 40,000 CC events in order to have sufficient statistical power. At a distance scale of 730 km from the accelerator (the Soudan site), this would require about 16 KT of mass for 2 years of running (10^7 seconds per year) assuming 5×10^{13} protons per pulse with a 1.9 s repetition rate. Since the flux scales inversely to the distance squared, the same statistics could be gleaned from a detector of roughly 9 KT if located 570 km from the accelerator (the former IMB site) or alternatively larger statistics could be acquired with a detector of equal size. Clear appearance signatures will benefit from even higher statistics. In any case, we set 10 KT as the minimum mass for this detector and depending on constraints from the location, technology and costs as much as 25 KT might be achievable. We envision two major divisions in calorimeter technology which can be employed:

- A gas-sampling calorimeter with alternate planes of absorber and readout devices. The detector elements could consist of resistive plate counters (RPC's) or some type of proportional/streamer tube system. In any case, it is envisioned that readout will be based on strips rather than pads in order to keep the number of readout channels to a reasonable number. RPC's are attractive from the viewpoint of ease of construction, possible low cost and their very good time resolution properties. Good time resolution is useful for maximizing the fiducial volume of the detector by positively identifiying whether an event which is only partially contained (an exiting muon for instance) had the interaction vertex within the calorimeter. This will be especially important for atmospheric neutrino measurements and could also be useful for other measurements on down-going multiple muon events. A proportional or streamer tube system could be viewed either as a backup approach or as part of a hybrid solution in case some fundamental difficulty is encountered with development of appropriate RPC's. Further development work on RPC's is important. The rate capability of these detectors is a well known difficulty for accelerator experiments but they may be very well suited to the low rate environment of an underground laboratory. However, RPC's have never been used in an application where the analog response is important. Some initial work on testing RPC's [7, 8] in a calorimeter has been done by some of us but further development and tests will be essential.

- A scintillating fiber calorimeter based either on alternating planes of absorber and fibers or on crossed planes of fibers encased in a surrounding concrete-like absorber medium. (This possibility is an extension of an idea proposed by Barbarino [9].) Here, the scintillating fibers within a plane could be summed together in strips for readout with the same granularity as a gas-sampling calorimeter. However, the scintillating fibers could supply two distinct advantages. First, the fiber readout will not be subject to the intrinsic fluctuations of detector response of gas-sampling devices. This can improve the energy resolution for both electromagnetic and hadronic showers. Second, in the case of the concrete-encased fibers, it will be possible to make planes of fibers in any desired direction (not just in between layers of absorber). In this case, the acceptance of the detector can be much more isotropic which can be useful for atmospheric neutrinos or an accelerator beam coming from some different direction. Finally, in this case it may be possible to achieve a relatively finer-grained longitudinal sampling by distributing fibers throughout the absorber medium. Research and development work is needed to study what lengths of fibers can be employed, optimization of the tubes and multiplexing (and what implications this could have on the fiber lengths and physics) , determination of possible problems with the stray magnetic fields affecting the tubes, etc.

There are several issues which are common to either of the fundamental approaches presented above. First, the material and thickness of the absorbers can be tuned according to physics goals and/or physical or financial constraints on the detector. For instance, lower density, low Z materials will permit the best opportunity for measurements on electromagnetic showers and separation of π^0's from electrons. However, high density, high Z materials will allow larger total mass for a fixed number of detector elements. Further, a high fraction of iron will allow for easy magnetization which is an attractive option for measurement of muon momentum. From preliminary studies, it is our expectation that the latter arguments win out and hence we propose here a detector based either on iron plates for the absorbers or on a concrete-like material loaded with as much iron as possible. Preliminary studies show that the best thickness for the iron plates is between 2 and 4 cm (of pure iron or steel). In optimizing the final design for the absorbers, it will be necessary to consider whether a new underground cavern is assumed or an existing cavern will be used.

We propose two views for the readout. These views could either be in each plane or with the different views in alternating planes in order to keep the number of channels fixed while increasing the frequency of longitudinal sampling. The orientation of the two views with respect to each other must be studied carefully in order to arrive at the best stereo angle for the expected density of particles in the neutrino interactions. Studies have shown that a 2 cm pitch for the readout strips gives reasonable separation and resolution for tracking. More studies will be necessary before a final pitch is decided. For the scintillating fiber option, the best isotropy would be achieved by having two different sets of fibers which would cross in planes which are perpendicular to each other. The construction of this device would likely present some technical challenges but shouldn't prove too difficult. Of greater concern is the roughly doubling of the active detector and electronics cost if one assumes equal granularity in each of the crossing views.

We believe that measurement of muon momentum is a very important feature for a detector in a ν_μ beam. This is the only way that one can really be certain of the differential flux with energy at the far detector. Knowledge of this measurement permits sensitivity to oscillations but it is also essential for any sort of measurement to verify that the pointing and calculation of the beam spectrum is correct. Otherwise, every measurement will always rest on a calculation of the neutrino flux... calculations which have never been proven on the distance scales which we envision. Because the distance scales are so much greater than previous neutrino experiments, very subtle divergences in the beam which are of no consequence to the near detector can have a dramatic effect on the far detector. The only way to know that there is no effect of this sort is to prove it by measuring the beam at the far detector! Hence, we expect that we will include means for muon momentum measurement in any final detector design. For muons with momenta of a few GeV (perhaps up to 10 GeV for a sufficiently long detector) the best means of measuring the momentum is by ranging the muons out in the material of the detector. For higher momenta and to allow for maximal fiducial volume of the detector, a magnetic field is essential. In the detector based on iron plates for absorbers, the means of producing this field is obvious; the plates have a coil wound through the center making the entire detector a large toroidal magnet. The same approach could be taken with the scintillating fiber in 'concrete' detector as long as the concrete is sufficiently loaded with iron to be easily magnetized. It could be possible to build a non-magnetic calorimeter followed by a separate toroidal magnet if this proves a superior approach. For now, we envision that the whole detector acts as the magnet.

Although it *may* be possible to overcome background difficulties with a surface detector for a beam experiment, a surface detector would not have any ability to study atmospheric neutrino events or other possible topics available in the underground environment. For a Fermilab beam, we know of two possible underground sites that could be used for construction of this detector. The former IMB site has a cavern which is roughly a cube with sides of 20 m. Using 4 cm iron plates (assuming 2 cm gaps for detectors), a detector of up to 25 KT would fit comfortably in this site while with 2 cm iron plates the mass could be 19 KT. The Soudan site has an additional area next to the exisiting Soudan II detector which is 26 m long by 12 m wide by 11 m high which could comfortably accomodate a detector of 11 KT with 4 cm plates or 8 KT with 2 cm plates. However, in the case of the Soudan site, the beam arrives at 40° with respect to the long axis of the hall. Construction ease likely mandates plates aligned transversely to this axis which means that instead of 4 cm maximum thickness plates we would demand plate thickness of no more than 3 cm, limiting the maximum mass to 10 KT. Hence we expect that it actually saves money to build a new cavern at Soudan with the axis alligned to point towards Fermilab in order to reduce the necessary number of active elements in the detector. Hence we, take that as the default approach at this site. The Soudan site has the advantage of the smaller but finer-grained Soudan II detector which could be exposed to the neutrino beam simultaneously if this site were chosen. On the other hand the already existing former IMB site is larger and some earlier studies have shown that the beam may be less expensive if aimed towards this site than the Soudan site [4].

In order to keep systematic errors sufficiently low so that we can take advantage of the high statistics permitted with the large detector, we find that a near detector is very desirable. For purposes of studying systematic errors, a near detector should be built with nearly the same characteristics as the far detector, just smaller. This will require a near experimental hall on the Fermilab site to accomodate a detector with transverse dimensions of at least $3m \times 3m$ and $10m$ in length.

Finally, as will be discussed in the following section, preliminary studies show that a narrow-band neutrino beam can add very interesting possibilities for unambiguous ν_τ appearance signatures by using

Osc. type→ $\Delta m^2(eV^2)$ → $\sin^2 2\theta$ → event type or ratio	No Osc.	$\nu_\mu \leftrightarrow \nu_e$ .01 .4	$\nu_\mu \leftrightarrow \nu_\tau$ .001 .87	$\nu_\mu \leftrightarrow \nu_\tau$ .008 .87	$\nu_\mu \leftrightarrow$ sterile ν .008 .87
'muon-like'	812 ± 28	690 ± 26	620 ± 25	620 ± 25	160 ± 13
'electron-like'	460 ± 21	580 ± 24	450 ± 21	450 ± 21	410 ± 21
'hadron-like'	308 ± 18	320 ± 18	310 ± 18	340 ± 18	220 ± 15
h-like/μ-like	$.38 \pm .03$	$.46 \pm .03$	$.44 \pm .03$	$.54 \pm .04$	$.35 \pm .03$

Table 1: Number of events in a 60 KT-year exposure for atmospheric ν's for various oscillation hypotheses. The errors shown are one σ statistical errors only. It is expected that there will be systematic errors of about 8% for the 'hadron-like' sample of events and 2% for the energetic muon and 'electron-like' event samples.

kinematic constraints on the leptonic τ decays. Hence we believe a study should be initiated with Fermilab on the possibility of building the beamline to allow for both a broad-band and narrow-band mode of operation. The broad-band beam itself needs study of possible options, including horns with plugs and perhaps quadrupole beams to optimize the spectrum and reduce backgrounds. The goal of the experiment is to maximize sensitivity to oscillation parameters, not maximize neutrino flux at the far detector. Because horn-focussed beams maximize flux primarily by including a high-energy tail, this can actually add to background for very small Δm^2. We expect that the two beams can use the same optics and decay tunnels with the only significant additional cost being to build a wider tunnel where the optics will be housed. The decay tunnel should be unaffected.

3 Physics Studies with a 17 KT Iron Calorimeter

Here, we present results of some studies of physics capabilities using a 17 KT detector with a fiducial mass of 15 KT. The purpose of this section is to illustrate some of the possibilities which can be achieved with a detector of this sort. It is not a statement that this is necessarily the preferred construction. The detector is assumed to be based on 4 cm iron absorber plates with 2 cm wide strips for readout. Depending on the specifics of the layout, this results in roughly 500,000 channels of strips to be readout and 50,000 m^2 of detector. A sketch of this layout is shown in figure 1. It is assumed that the iron is magnetized toroidally with a field of 20 KGauss inside of the plates. It is assumed that the beam is perpendicularly incident on the plates and that the detector is located 720 km from the accelerator. For studies of the ability to separate different types of events a GEANT simulation of the detector has been used. The acceptance of the detector for atmospheric neutrinos is taken to be 2π steradians ($\pm 60°$ from the horizontal). The atmospheric neutrino flux which has been used is the recent 'Bartol' flux of Gaisser and Stanev [5] with explicit integration over zenith angles and pathlengths for different oscillation hypotheses.

The detector makes use of topologies of contained events to identify different types of neutrino interactions on a statistical basis. Monte Carlo events are classified as 'muon-like' (containing a long muon track), 'electron-like' (a short, showering event primarily from ν_e interactions), 'hadron-like' (a long showering event with no clear muon track; primarily NC interactions) or 'other'. The selection criteria used here are generally most efficient for neutrinos with energies greater than about 3 GeV. Table 1 shows the number of events and ratios of event types for a 60 KT-year exposure for atmospheric neutrinos for various oscillation hypotheses. Table 2 shows the number of events and ratios for 1 year

Osc. type→ $\Delta m^2(eV^2)$ → $\sin^2 2\theta$ → event type or ratio	No Osc.	$\nu_\mu \leftrightarrow \nu_\tau$ .001 .87	$\nu_\mu \leftrightarrow \nu_\tau$ .008 .87	$\nu_\mu \leftrightarrow \nu_\tau$ .08 .87	$\nu_\mu \leftrightarrow$ sterile ν .008 .87
Main Injector beam with detector at IMB site (570 km)					
ν_μ events	41000	40800	32900	23900	32900
CC ν_τ events	0	25	1360	4520	0
'muon-like'	30300 ± 170	30200 ± 170	22300 ± 150	16200 ± 130	22300 ± 150
'hadron-like'	10700 ± 100	10600 ± 100	11400 ± 110	13800 ± 120	7830 ± 89
h-like/μ-like	$.353 \pm .004$	$.351 \pm .004$	$.511 \pm .006$	$.851 \pm .010$	$.351 \pm .005$
Main Injector beam with detector at Soudan (730 km)					
ν_μ events	25000	24800	18100	15600	18100
CC ν_τ events	0	25	1250	2520	0
'muon-like'	18500 ± 140	18300 ± 140	13400 ± 120	11500 ± 110	13400 ± 120
'hadron-like'	6500 ± 80	6500 ± 80	7270 ± 85	8250 ± 90	4700 ± 70
h-like/μ-like	$.351 \pm .005$	$.355 \pm .005$	$.543 \pm .008$	$.717 \pm .010$	$.351 \pm .007$
450 GeV SPS beam with detector at Gran Sasso (720 km)					
ν_μ events	20000	20000	18200	8740	18200
CC ν_τ events	0	8	475	5150	0
'muon-like'	14800 ± 120	14800 ± 120	13500 ± 120	6480 ± 80	13500 ± 120
'hadron-like'	5200 ± 70	5200 ± 70	5450 ± 70	9050 ± 95	4740 ± 70
h-like/μ-like	$.351 \pm .006$	$.351 \pm .006$	$.404 \pm .006$	$1.40 \pm .020$	$.351 \pm .008$

Table 2: Number of events in a 1-year accelerator run (with a wide-band beam with accelerator and detector as shown) and ratios for 'muon-like' and 'hadron-like' events for various oscillation hypotheses. The errors shown are statistical only. Systematic errors should be on the order of 1% for the h-like/μ-like ratio once the acceptance is corrected using the near detector.

of running with an accelerator beam with the detector and beam configuration as noted. The regions of parameter space for ν_μ to ν_τ oscillations which can be ruled out at the 90% confidence level using the ratio of 'hadron-like' events (nominally NC) to 'muon-like' events is shown in figure 2. Also shown in figure 2 is the region of parameter space which can be ruled out for ν_μ to ν_e oscillations based on the ratio of 'electron-like' to 'muon-like' events. The limits for the accelerator beam shown for this mixing are made assuming that a lower energy neutrino beam (most probable energy of 4 GeV) would be used than is necessary for the neutral current to charged current ratio measurement. We expect that the systematic errors for this detector will for the most part be comparable to those in the Soudan II detector for P822 as outlined in their report to the Fermilab PAC in March, 1994 [10]. The systematic errors for most measurements will be less than about 1%. The ability to pick-out and measure events with an electron will be poorer than in the Soudan II detector due to the coarser sampling in the larger detector.

We have begun to study possible means of unambiguous signatures of ν_τ appearance. Although very preliminary, the studies suggest that we should be able to provide identification signatures. One possibility is to use quasi-elastic events and make kinematic cuts looking for anomalous transverse momentum in the resulting leptons. The best signature which we have been able to identify thus far is based on the use of a narrow-band beam. Given knowledge of the neutrino energy, it is possible to make

Osc. type→	No Osc.	$\nu_\mu \leftrightarrow \nu_\tau$	$\nu_\mu \leftrightarrow \nu_\tau$	No Osc.	$\nu_\mu \leftrightarrow \nu_\tau$	$\nu_\mu \leftrightarrow \nu_\tau$
$\Delta m^2 (eV^2) \rightarrow$		.08	.008		.08	.008
$\sin^2 2\theta = 1$						
event type	Fermilab MI Beam			CERN SPS Beam		
ν_μ CC	4000	2000	2140	4000	2600	3200
ν_τ CC	0	910	320	0	1480	140
$\tau \rightarrow \mu\nu\nu$	0	160	54	0	250	24
$\tau \rightarrow \mu\nu\nu$ after cuts	0	18	8	0	63	4

Table 3: Number of events using a narrow-band beam and the number of ν_τ CC events remaining after removing all ν_μ background. The detector distance is 720 km in both cases.

kinematic cuts for events with τ decaying to μ which allows a statistical identification of the ν_τ events. There is a trade-off in use of these two approaches. The narrow-band beam gives a smaller flux but the knowledge of the beam energy gives a valuable kinematic constraint allowing for less stringent analysis cuts. The approach using quasi-elastic events allows use of the broad-band beam but requires stringent analysis cuts to select the appropriate sample of events. Further study is required to determine the best strategy to pursue if some hint of oscillations is observed.

For our study on use of a narrow-band beam, we assume that the energy of the neutrino beam has been optimized for a particular Δm^2. All detector and beam smearing effects are included in the calculation. We define three experimental kinematic parameters: y_{exp} is the fraction of the initial neutrino energy that is observed in the detector in electromagnetic and hadronic showers, $1 - y^{\mu}_{exp}$ is the fraction of the initial neutrino energy carried away by the scattered muon and θ_{lab} is the scattering angle of the muon away from the neutrino direction in the laboratory frame. Figure 3 shows scatter plots for y_{exp} vs $1 - y^{\mu}_{exp}$ while figure 2 shows the scatter plot for $1 - y^{\mu}_{exp}$ vs θ_{lab}. Clearly, the distributions for ν_μ CC events and ν_τ CC events populate significantly different regions of the parameter space for these variables. The cuts used for the analysis are shown on these plots. It should be noted that the cut positions depend on the number of ν_μ CC events that are actually observed. Table 3 shows the number of events expected for approximately 2 years of running for a narrow-band beam with a 15% sigma momentum-bite and the number of ν_τ CC events which remain with less than 1 event of background from ν_μ interactions. More study needs to be done to get a better understanding of the rates that this approach can allow. In particular, only a very rough estimate of the flux in this type of beam has been used (the assumption is that a beam of this type will have a factor of 10 less flux than a wide-band beam).

4 Cost Estimate

Clearly, given the range of options in the construction, there will also be a range of options in the cost of the detector. The major costs assuming a detector based on RPC's is as follows:

1. Steel for the absorbers. The cost for this steel will be roughly \$.5M per KT. For the 17 KT detector, total cost is \$9M. Note that it may be possible to significantly reduce this cost using a 'creative' means of acquiring the steel such as 'borrowing' the steel for a number of years.

2. Planes of detectors. The cost for RPC's is estimated to be between \$100-\$200 per m^2 for construction of areas on this scale. For the nominal 17 KT detector with 4 cm absorbers, roughly 50,000 m^2 are required which would cost between \$5M-\$10M. Streamer tubes would likely cost

about the same as the high-side number.

3. Distributed Electronics: We believe that the electronics for this detector can cost substantially less per channel than the normal 'typical detector electronics'. The reason for this is that the detector is not trying to perform very precise measurements of energy as is the case for many accelerator-based calorimeters. Electronics which provide a precision in charge measurement to 10% will be adequate. Furthermore, the electronics will work in a low rate environment so high-rate capabilities are unnecessary. Good timing electronics is desired but this need be performed only over sums of adjacent strips. Some of us have already tested electronics designed especially for RPC's based on discrete components at a cost of approximately $20 per strip of readout. We expect that a final design would use a specially designed chip which will almost certainly drive the cost to no more than about $10 per strip for readout. The price could be as low as $5 per strip but at this point the cost of cables and connections starts to dominate. For the nominal design there are .5M channels of readout for a cost of $5M.

4. General electronics. We estimate that the cost for HV supplies, low voltage supplies, interface electronics and general trigger and logic electronics will be no more than about $1M.

5. Data acquisition system. We expect that the required data acquisition system will be modest due to the low rate environment. We estimate that the full data acquisition system should cost no more than $.5M.

6. Gas system. RPC's require a stable gas mixture which is typically composed of argon, isobutane and a small amount of Freon. We estimate that the cost of the gas system will be about $1M.

7. Magnet coil and power supply. Because it is iron which is being magnetized and not free space, the coil does not have to carry a particularly large amount of current. We estimate that the cost of the coil and power supply will be approximately $1M.

8. Site preparation. We estimate that the minimum cost for site preparation (regardless of location) will be approximately $.5M.

Hence, the total cost for such a detector is estimated to be $28M with potential for savings in the detectors, steel and distributed electronics which could conceivably bring the cost down. This cost appears reasonably matched to the laboratory investment in the neutrino beam.

As pointed out earlier, the scintillating fiber option could nominally look exactly like the RPC option only replacing the RPC's and strips with fibers and phototubes. Presumably, the rest of the detector would cost about the same. The cost for scintillating fibers with 2mm diameter for large amounts is about $.25 per m. This translates to $150 per m^2 for a planar geometry. Hence, the cost for fibers would be about $10M. We assume small, inexpensive phototubes for the readout at a cost of $100 apiece. Clearly, some multiplexing is required for this option. Assuming multiplexing of 5 to 1, the cost for phototubes would be $10M. Hence, the total cost for the nominal detector based on scintillating fiber technology would be about $37M.

This gives the scale of the resources required for a detector to meet the goals we state. A better estimate can be made only following the major technical decisions and some value engineering. The cost for other options such as a more finely-grained detector or with crossed planes of fibers can simply be scaled based on the unit costs in the preceding paragraphs. If a new cavern is required for construction of the detector, it is estimated that this would add between $3-5M to the cost.

5 Comparison with Other Detectors

The following are some points of comparison with other proposed experiments for long-baseline oscillation measurements compared to the capabilities of the experiment described here. Figure 5 compares the various limits for oscillation parameters.

- This detector at the Gran Sasso using a CERN beam: It is the intent of this collaboration to submit a proposal parallel to this one at the Gran Sasso Laboratory and CERN for construction of this detector in the remaining part of Hall B. The reason for submitting these proposals in parallel is that pursuing this line of research will involve a major decision and undertaking for either CERN or Fermilab. The general goals can be met at either location and we feel both should be explored at this early EOI stage. We expect that the full collaboration will commit to one proposal or the other once the laboratories have made clear their interest and commitment to this research.

  For comparison, we note that the CERN SPS cannot deliver as many protons as the Fermilab Main Injector. However, if the highest possible proton energies are used (450 GeV) then the flux of ν's at the Gran Sasso is roughly equivalent to the flux of neutrinos at Soudan using the Main Injector. Since the distances are almost exactly the same, detectors at the Gran Sasso will have slightly less reach in Δm^2 than at Soudan but for sufficiently large Δm^2 will have better sensitivity for τ appearance than using the Fermilab beam due to the relatively higher ν_τ cross section with the SPS beam.

- Super-Kamiokande. The Super-Kamiokande detector is now under construction in Japan. A low-energy neutrino beam has been proposed to be aimed towards Super-Kamiokande from KEK. This experiment would rely on the ratio of ν_μ CC events in a near detector versus the far detector for $\nu_\mu - \nu_\tau$ oscillations and the appearance of ν_e's for $\nu_\mu - \nu_\tau$ oscillations. The neutrino energy is below that required for any τ appearance experiment.

- Brookhaven E889. This experiment is similar to that proposed by KEK but with the 'far' detector much closer to the accelerator in order to give a sufficient rate without as much total mass as Super-Kamiokande. Once again, no signature of τ appearance is possible. In addition, we believe that it is difficult to understand the systematic errors of the calculation of the 'far' beam in this case.

- ICARUS. The ICARUS detector has been proposed at the Gran Sasso. Aside from issues such as cost, time scale and potential construction difficulties, a first-round ICARUS would be 5 KT with excellent imaging capabilities and very good energy resolution for electrons and photons (with a partial ability to separate π^0s from electrons). No ability to measure GeV muon momenta has been proposed for this detector thus far. The lack of muon momentum measurement, smaller containment volume for hadrons and the smaller mass are the main disadvantages of the ICARUS detector compared to this detector for this measurement. ICARUS will have better energy resolution and identification for electrons. As for this detector at the Gran Sasso, the neutrino flux is smaller than at Fermilab except when using the highest energy primary protons possible from the SPS.

- Reactors. Two small reactor neutrino experiments have been proposed and are in the final stages of preparing for construction. One is located in France at the Chooz reactors and the other in Southern California at the San Onofre reactors. By utilizing the very low energies and high flux of neutrinos from the reactors, these experiments can test for the hypothesis of $\nu_\mu - \nu_e$ oscillations in the region of the atmospheric anomaly. They are limited in their reach in $\sin^2 2\theta$ to about .1 from both statistical and systematic error.

- Surface Water Cerenkov with high-energy (Fermilab or CERN) beams. These proposals may be interesting for offering very large detector masses at large distances from the accelerator, nominally offering sufficient statistics to reach very small Δm^2. However, it will not be possible to build these detectors so that many different physics signatures will be available. This could lead to unknown systematic error problems which will limit the ultimate sensitivity.

- Deep water Cerenkov with high-energy (Fermilab or CERN) beams. There are currently 4 large underwater Cerenkov detectors under construction; DUMAND near Hawaii, AMANDA at the South Pole, NESTOR off the coast of Greece and the Lake Baikal Cerenkov detector. These detectors have the advantage of very large target masses allowing high statistics. However, they generally have rather high threshold for muon events due to sparse location of phototubes. This also makes it very difficult to do reliable identification of different types of neutrino interactions so that it is anticipated that only a ν_μ disappearance experiment would be possible.

6 Resources Needed to Develop an LOI

In order to develop a Letter of Intent for construction of the this detector, we must systematically work through the various technical options described in this note. Much of that work will involve Monte Carlo analysis. However, there are fundamental questions about the type of detector element to use which can only be answered by further detector studies. In particular, for the case of RPC's, we feel that further study of the analog response is important. This is especially true for the response to electromagnetic showers for which we do not yet have clear evidence that we understand the response. (A test of a prototype RPC calorimeter was performed at CERN in November, 1993 by some of us. The analysis is still in progress.) Further prototype development work is needed for either of the major options outlined in this note. In addition, engineering and costing studies will be necesary for the detector and civil engineering for particular sites. We estimate that approximately $500K in support and one year of work is required to arrive at the Letter of Intent stage. Part of this support could be supplied by Fermilab personnel. We will need mechanical and civil engineering support for helping to determine costs and feasibility for the various site and construction options. Once some of the major decisions are made on the detector technology, further engineering support will be necessary to arrive at a detector design. In particular, we would need one dedicated mechanical engineer, 1 dedicated electrical engineer and 1 costing/scheduling specialist. We expect that we would work with Fermilab beam experts to further understand the options and possibilities in the beam. We emphasize again that an important possibility for τ appearance could come with the use of a narrow-band beam. Hence, we request that Fermilab study the possibility of including such a beam in the civil construction and development plans.

7 Resources Needed for Construction of Detector

We believe that it is essential that this detector be ready to run when the beam is completed. The scale of this detector is less than that of MACRO but there are two detectors (near and far) to be built. Although the near detector is much smaller than the far detector, we do not think that makes it only a small extra effort. Based on our experience with MACRO, we estimate that a collaboration of approximately 100 collaborators could complete this detector in a 5 year period. The proposing group forms a good basis for building such a collaboration.

References

[1] Hirata, K.S., *et al.*, Phys. Let. **B280** (1992) 146.

[2] Casper, D. *et al.*, PRL **66(20)** (1991) 2561.

[3] Brun, R. *et al.*, CERN report DD/EE84-1, 1987.

[4] Bernstein, R. *et al.*, Conceptual Design report: Main Injector Neutrino Program, Fermilab, 1991.

[5] T.K. Gaisser, private communication.

[6] Michael, D.G., Searching for Oscillations of Atmospheric and Accelerator Neutrinos, Caltech-68-1827, Aug. 1992, unpublished.

[7] C. Gustavino, etal. A modulear design for glass spark counters, LNF-93/074, submitted to NIM A.

[8] D. Michael et al, private communication.

[9] Barbarino, G., private communication.

[10] P822 Collaboration, W. Allison et. al., Proposal Update to Fermilab PAC, March, 1994.

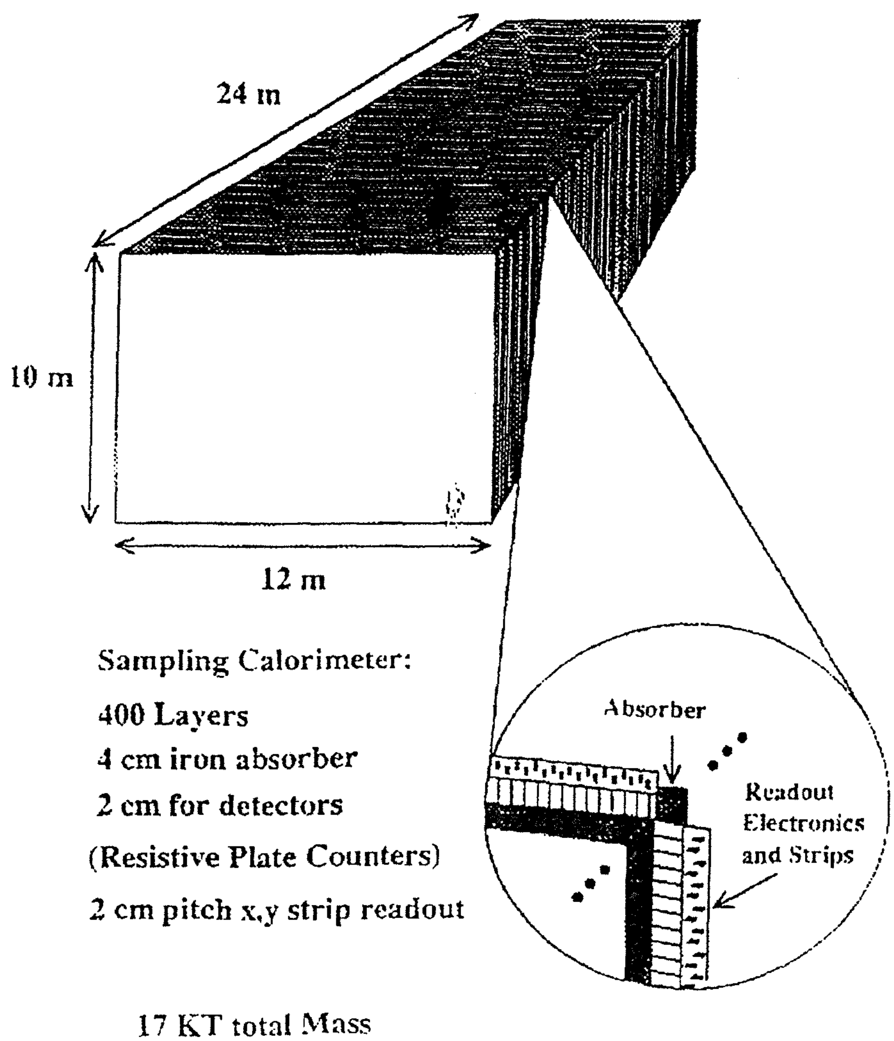

Figure 1: Sketch of one possible detector configuration.

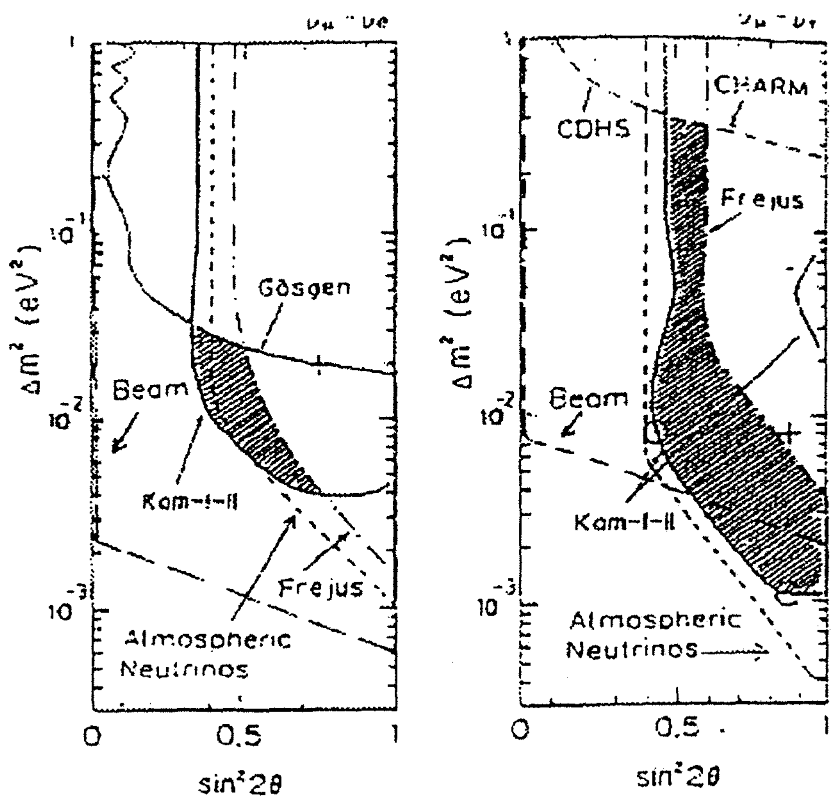

Figure 2: Areas of oscillation parameter space ruled out at the 90% confidence level based on NC/CC ratio compared to allowed regions of parameter space based on Kamiokande results.

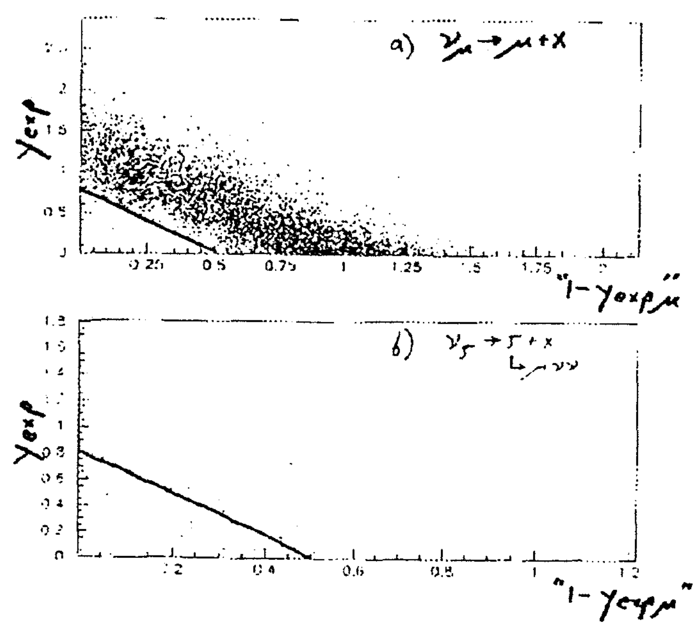

Figure 3: Scatter plot of y_{exp} vs $1 - y^{\mu}_{exp}$ for a) ν_μ CC events and b) ν_τ CC events. Lines show cuts used in analysis. See text for further description.

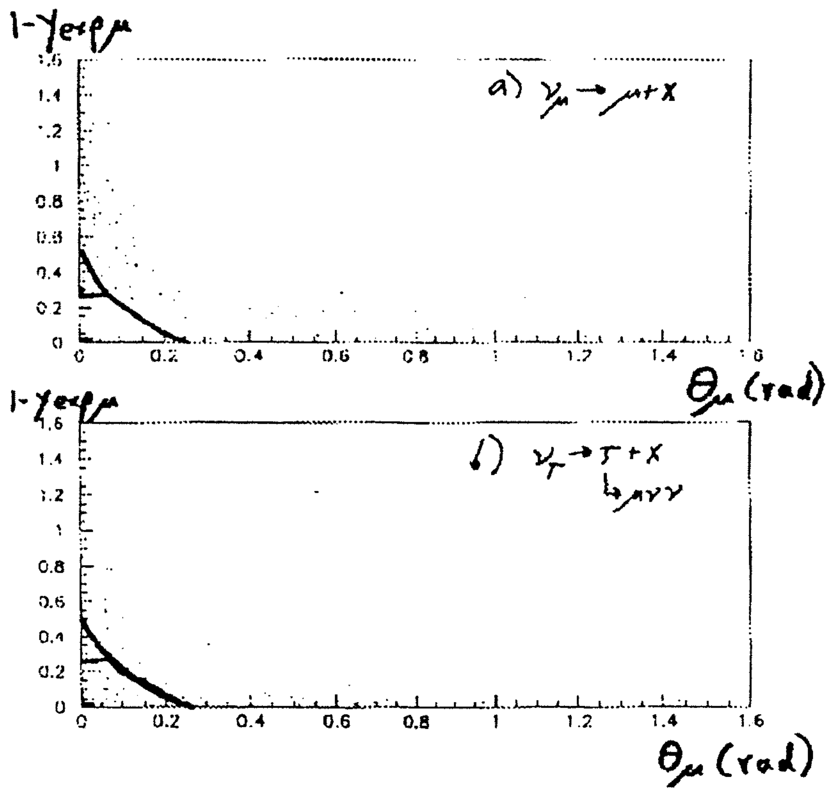

Figure 4: Scatter plot of θ_{lab} vs $1 - y^{\mu}_{exp}$ for a) ν_μ CC events and b) ν_τ CC events. Lines show cuts used in analysis. See text for further description.

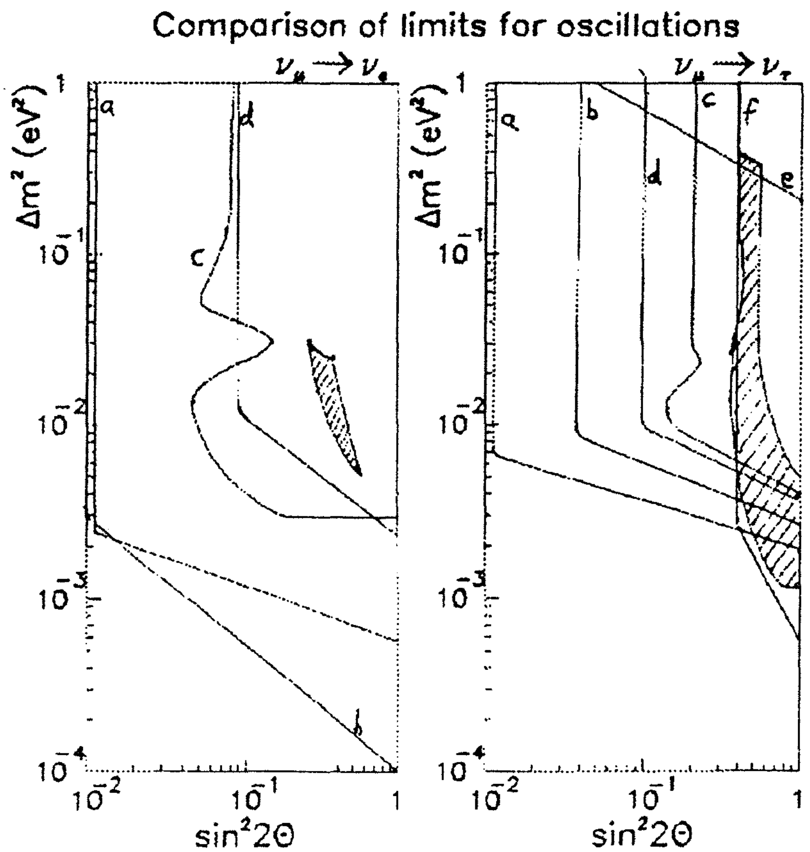

Figure 5: Comparison of areas of oscillation parameter space ruled out at the 90% confidence level for different proposed experiments: a) this experiment, b) ICARUS (horn beam) c) Super-Kamiokande d) Brookhaven E889 or Fermilab P822 (for ν_μ to ν_τ using ratio of NC/CC events), e) Fermilab E803 (similar for CHORUS and NOMAD), f) this experiment using atmospheric neutrinos. Note that many different assumptions about technique and beams have gone into these different curves which can make exact comparison difficult. These limits are approximate and should only give an idea of the different regions of parameter space which are covered.